The Runaway Electron Benign Termination Scenario: Physics Processes and Operational Limits

C. Reux[1], U. Sheikh[2], C. Paz-Soldan[3], O. Ficker[4], M. Lehnen[5], S. Jachmich[5], S. Silburn[6], P. J. Lomas[6], C. Lowry[6], N. Schoonheere[1], D. Craven[6], J. Wilson[6], M. Nocente[7], A. Dal Molin[7], G. Szepesi[6], D. Kos[6], A. Boboc[6], A. Lvovskiy[8], M. Baruzzo[9], A. Hakola[10], E. Joffrin[1], C; Sommariva[2], A. Battey[3], D. Brunetti[6], P. Buratti[9], H. Choudhury[3], J. Decker[2], N. Eidietis[8], M. Hoppe[11], H. Isliker[12], E. Kowalska-Strzeciwilk[13], G. Marcer[7], E. Nardon[1], V. Plyusnin[14], D. Rigamonti[15], L. Spolladore[16], E. Tomesova[4], M. Zerbini[9], JET contributors* and the Eurofusion Tokamak Exploitation Team§

[1]CEA, IRFM, F-13108 Saint-Paul-les-Durance, France, [2]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland, [3]Department of Applied Physics and Applied Mathematics, Columbia University, New York 10027, USA, [4]Institute of Plasma Physics of the CAS, Za Slovankou 1782/3, 182 00 Praha 8, Czech Republic, [5]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046 - 13067 St Paul Lez Durance Cedex France, [6]UKAEA, Culham Campus, Abingdon, OX14 3DB, UK. , [7]University Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy, [8]General Atomics, PO Box 85608, San Diego, CA 92186-5608, United States of America, [9]Fusion and Nuclear Safety Department - ENEA C. R. Frascati - Frascati (Roma), Italy., [10]VTT Technical Research Centre of Finland Ltd, PO Box 1000, FIN-02044 VTT, Espoo, Finland, [11]KTH Royal Institute of Technology, Division of Electromagnetic Engineering and Fusion Science SE-100 44 Stockholm, Sweden, [12]Department of Physics, Aristotle University of Thessaloniki, 541 24 Thessaloniki, Greece, [13]Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland, [14]Instituto de Plasmas e Fusao Nuclear, Instituto Superior T'ecnico, Universidade de Lisboa, Portugal, [15]Istituto per la Scienza e Tecnologia dei Plasmi, ISTP-CNR, via R. Cozzi 53, 20125 Milano, Italy, [16]Università di Roma Tor Vergata, Via del Politecnico 1, Roma, Italy

Runaway electron (RE) beams may form during tokamak disruptions with electron energies up to several MeV and may reach multi-MA currents in large devices. Since preventing post-disruption REs completely is not always possible, a second line of defence is required. A scenario to terminate a RE beam benignly was discovered on DIII-D [1] and JET [2]. It consists in injecting large amounts of hydrogen or deuterium into a RE beam. This provokes the recombination of the companion plasma co-existing with REs. The collapse of the beam becomes completely benign without measurable heat loads on plasma-facing components. This behaviour is likely due to a combination of a large and fast MHD instability and the absence of regeneration of REs during the beam final collapse.

For this to be extrapolated to ITER, the conditions under which this scenario is effective need to be understood. Recent experiments at JET have shown that the composition of the companion plasma is essential for the mitigation success. A low ratio of high-Z impurities (mostly argon, used to trigger the disruption) to hydrogenic material (H_2 or D_2) is needed to achieve benign termination. Too much argon leads to the regeneration of a small RE beam during the final collapse. If even more argon is present, an incomplete disappearance of REs is observed, sometimes with reionization of the companion plasma. An otherwise non-benign termination can be cured by injecting additional hydrogenic material, up to a certain point. Too much hydrogenic material increases the collision rate of REs up to a point where a benign termination is no longer possible. Higher pre-disruption currents (up to 3.0 MA at JET) were also found to require more hydrogenic material to achieve benign termination, as observed on ASDEX Upgrade. The picture is complex as higher pre-disruptive currents are also associated with larger vertical instability, higher MHD activity, higher RE currents and energy. Extrapolation of the required hydrogenic amount as a function of the pre-disruption plasma and companion plasma parameters is discussed. Runaway regeneration physics during the collapse as well as the influence of MHD activity on the RE dissipation are also addressed.

[1] Paz-Soldan et al., PPCF 61 054001 (2019), [2] Reux et al., PRL 126 175001 (2021).

* See J. Mailloux et al. Nucl. Fusion **62** (2022) 042026. §See E. Joffrin et al. To be published in Nucl. Fusion.